No-Scale Scenarios in the Light of New Measurement of Muon Anomalous Magnetic Moment

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Abstract

Supersymmetric contribution to the muon anomalous magnetic moment a_μ is discussed in the no-scale-type supersymmetry breaking scenarios. Taking the correlation between the supersymmetric contributions to a_μ and $Br(b \to s\gamma)$, it is shown that the precise measurements of these quantities serve an important constraint on the relative sign of the gaugino masses; combining the 2.6-σ deviation in a_μ from the standard-model prediction measured by the E821 experiment and $Br(b \to s\gamma)$ measured by CLEO, the sign of the product $M_2 M_3$ is strongly preferred to be positive, where M_2 and M_3 are $SU(2)_L$ and $SU(3)_C$ gaugino mass parameters, respectively. In particular, no-scale-type models with universal gaugino masses are in accord with the two constraints and also with the Higgs mass bound. In addition, it is also shown that future improvements in the measurements of a_μ and $Br(b \to s\gamma)$ may provide serious test of the cases with $M_2 M_3 < 0$.

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Although supersymmetry (SUSY) is a promising candidate for the solution to the gauge hierarchy problem, issues of SUSY breaking and its mediation have been a long standing problem in SUSY model building. From phenomenological point of view, the mediation mechanism is of particular interest: it is what we will be able to probe in future collider experiments.

While superparticles may be too heavy to be directly produced at existing colliders, they will affect various physical quantities at loop levels. Among other things, quantities which are rather insensitive to assumptions on how to suppress SUSY flavor-changing-neutral-current (FCNC) contributions include a measured branching ratio $Br(b \to s\gamma)$ which is in good agreement with the standard-model prediction, the lightest Higgs mass m_h which is now bounded to be $m_h \geq 113.5$ GeV at LEP200 [1], and muon $g-2$ or muon anomalous magnetic moment $a_\mu \equiv (g-2)/2$ ([2] and references therein).

Recently, the Brookhaven E821 experiment reported the new measurement of the muon anomalous magnetic moment $a_\mu(\text{E821}) = 11\ 659\ 202\ (14)(6) \times 10^{-10}$ which is 2.6-σ away from the standard-model prediction $a_\mu(\text{SM})$ [3]. If we require that this anomaly be explained by the loop effects of the SUSY particles, it imposes non-trivial constraints on the MSSM parameters. (For recent discussions, see Refs. [4].) In this paper, we take this apparent deviation very seriously and consider it due to superparticle contributions

$$a_\mu(\text{SUSY}) = a_\mu(\text{E821}) - a_\mu(\text{SM}) = 43(16) \times 10^{-10}. \tag{1}$$

This can set upper bounds on superparticle masses, particularly on left-handed smuon and chargino masses, since the dominant contribution mostly comes from chargino-sneutrino loop. Importantly, the SUSY contribution to the muon $g-2$ is approximately proportional to $\tan\beta$, which is the ratio of the vacuum expectation values of the two Higgs bosons in the MSSM, and for not very large $\tan\beta \lesssim 10$, for e.g., the left-handed smuon is required to be relatively light, $m_{\tilde{\mu}} \lesssim 400$ GeV, at 2-σ level [5].

The upper bounds on the superparticle masses implied by $a_\mu(\text{SUSY})$ have interesting interplay with the other two quantities. First, in order to satisfy the Higgs mass bound of 113.5 GeV, large radiative corrections from top and scalar top (stop) loops are required. This argument suggests heavy stop quarks, in which case the large positive radiative corrections to the Higgs mass are expected. This should be contrasted with the light smuon required by the SUSY interpretation of a_μ. Thus the preferred pattern of superparticle mass spectrum is that sleptons are light while squarks are heavy.

Interplay with $Br(b \to s\gamma)$ is more subtle. It is known that the charged-Higgs contribution in the minimal supersymmetric standard model (MSSM) is always additive to the standard-model contribution, while the superparticle contribution can have either positive or negative sign. Since the measured branching ratio is consistent with the standard-model prediction, the charged-Higgs contribution should be cancelled by the other contributions. It is nontrivial whether the two requirements that the positiveness of $a_\mu(\text{SUSY})$ and the cancellation in $Br(b \to s\gamma)$ are simultaneously satisfied, and this will serve an important test of the mediation mechanisms of the SUSY breaking [6].

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In the framework of supergravity, tree-level SUSY breaking scalar masses are given as curvatures of scalar potential in supergravity Lagrangian. These masses are thought to be given at some high-energy renormalization scale close to the Planck scale or the GUT scale. The low energy values of the scalar masses are evaluated by renormalization group (RG) methods. Generally speaking, squarks acquire large positive masses squared due to RG effects from gluon-gluino loop while sleptons do not. Thus the squarks become much heavier than the sleptons especially when the tree-level masses coming from the supergravity interactions are small and the gaugino mass contributions from the RG effects dominate. As we mentioned above, this pattern of the superparticle mass spectrum is favored from the a_μ and the Higgs mass bound.

This argument leads us to consider an interesting scenario where the SUSY breaking scalar masses vanish at some high energy scale close to the GUT scale or the Planck scale. Such boundary conditions are called no-scale boundary conditions (see below for a precise definition) [7]. The purpose of the present paper is to study supersymmetric standard models with no-scale boundary conditions for SUSY breaking masses in the light of the new result on the muon anomalous magnetic moment. We will identify the preferred region for a_μ, taking into account other constraints such as the Higgs boson mass bound, superparticle mass bounds from direct searches, and the branching ratio $Br(b \to s\gamma)$. We do not impose the cosmological requirement that the lightest superparticle (LSP) should be neutral or constitute a dominant part of the dark matter of the Universe. This is in fact an appealing requirement, but not necessary: one can consider, for e.g., R-parity violation, light gravitino LSP, or other candidates for the dark matter.

We will consider the following Kähler potential in the supergravity:

$$K = -3 \ln[f(z, z^*) + g(y, y^*)], \tag{2}$$

where f is a function of hidden sector fields z responsible for SUSY breaking and g is a function of observable sector fields y including the MSSM. Here the reduced Planck scale has been set to unity. It turns out that SUSY breaking scalar masses as well as trilinear scalar couplings (so-called A-terms) vanish at the energy scale where the boundary conditions are given, as the vacuum expectation value of the scalar potential (*i.e.* the cosmological constant) vanishes. The form (2) can be traced back to the original no-scale model with a non-compact global symmetry [7]. The separation of the hidden sector from the observable sector in the form (2) was argued to be natural since it is obtained by the separation of the two sectors in the superspace density in the supergravity Lagrangian [8]. Interestingly it is geometrically realized in the setting of two separated 3-branes in 5-dimensional total spacetime (bulk), namely the hidden sector lives on one brane and the observable sector lives on another [9]. Gaugino masses can arise if, for instance, the gauge multiplets in the MSSM sector live in the bulk and the gauginos couple to the hidden sector brane directly (gaugino mediation) [10]. The no-scale boundary conditions should be set at the scale of the inverse of the 5-th dimension's length, which can be somewhat arbitrary.

The boundary conditions we will consider in this paper are therefore (i) vanishing

scalar masses, (ii) vanishing A-terms, and (iii) non-vanishing gaugino masses M_i^0 ($i = 1$, 2, 3) for three gauge groups $U(1)_Y$, $SU(2)_L$ and $SU(3)_C$. In addition, we assume that the higgsino mass parameter μ and Higgs mass mixing parameter (so-called B-parameter) are free parameters in our framework. The boundary conditions are given at some high energy scale $M_{\rm bc}$ which we assume to be at the GUT scale or above. For simplicity we take all the mass parameters to be real.

The superparticle mass spectrum is obtained by solving the RG equations. Specifically we consider particle contents of the MSSM. We impose the electroweak symmetry breaking condition to reproduce the correct Z boson mass for given $\tan\beta$. This constrains, for instance, μ and B in our setting. Thus the masses of the superparticles and Higgs bosons depend on M_i^0 ($i =$1, 2, 3), $\tan\beta$ and $M_{\rm bc}$.

Let us first consider the case where the gaugino masses are universal at the energy scale $M_{\rm bc}$. In this case due to RG effects their values at electroweak scale become approximately $M_1 : M_2 : M_3 \approx 1 : 2 : 6$. As we will see shortly, the relative sign of the gaugino masses is important when discussing the correlation between a_μ and $Br(b \to s\gamma)$.

In Fig. 1, contours of the constant a_μ(SUSY) are shown in the M_2 vs. $\tan\beta$ plane for the case of the universal gaugino masses. Here, the boundary conditions are given at $M_{\rm bc} = 2 \times 10^{16}$ GeV, and we take $\mu > 0$ (and $M_i > 0$) so that the SUSY loops give positive contributions to a_μ. In the same figure, we also present several other constraints, which were already discussed in Ref. [11]. First, we plot the contours of the constant m_h in the dash-dotted lines. In addition, we also show the parameter region consistent with the measured $Br(b \to s\gamma)$. In this analysis, we use the branching ratio measured by the CLEO experiment [12]:

$$Br(b \to s\gamma) = (3.15 \pm 0.35 \pm 0.32 \pm 0.26) \times 10^{-4}, \tag{3}$$

where the first (second, third) uncertainty is statistical (systematic, model dependence). Adding the uncertainties in quadrature, we obtained the 1-σ bound as $Br(b \to s\gamma) = (3.15 \pm 0.54) \times 10^{-4}$. Parameter region consistent with this 1-σ bound is shown by the darkly-shaded region in Fig. 1. In addition, the lightly-shaded region in Fig. 1 is the 95 % C.L. limit $2.0 \times 10^{-4} < Br(b \to s\gamma) < 4.5 \times 10^{-4}$ given by CLEO [12]. Remarkably one can find that the parameter region favored by the muon magnetic moment measurement is completely consistent with the allowed region by the other constraints. Notice that, even after imposing the Higgs mass bound of $m_h \geq 113.5$ GeV, wide parameter region remains.

In the no-scale-type models, the right-handed slepton masses are primarily from the $U(1)_Y$ gaugino mass. As a result, adopting the GUT relation among the gaugino masses, the right-handed sleptons become relatively light in this framework. This fact introduces other constraint on the no-scale-type models. Most importantly, the negative search for the sleptons at the LEP experiment sets a lower bound on M_2 since the slepton masses are increasing functions of M_2. In Fig. 1, this lower bound on M_2 is also shown. In fact, in some case, this bound is from the right-handed smuon, since the lightest stau mass $m_{\tilde{\tau}_1}$ is so close to the lightest neutralino mass m_{χ_1} that the decay products from the stau cannot be seen in the detector. In addition, it is well-known that, when $M_{\rm bc} \sim 10^{16}$ GeV, the
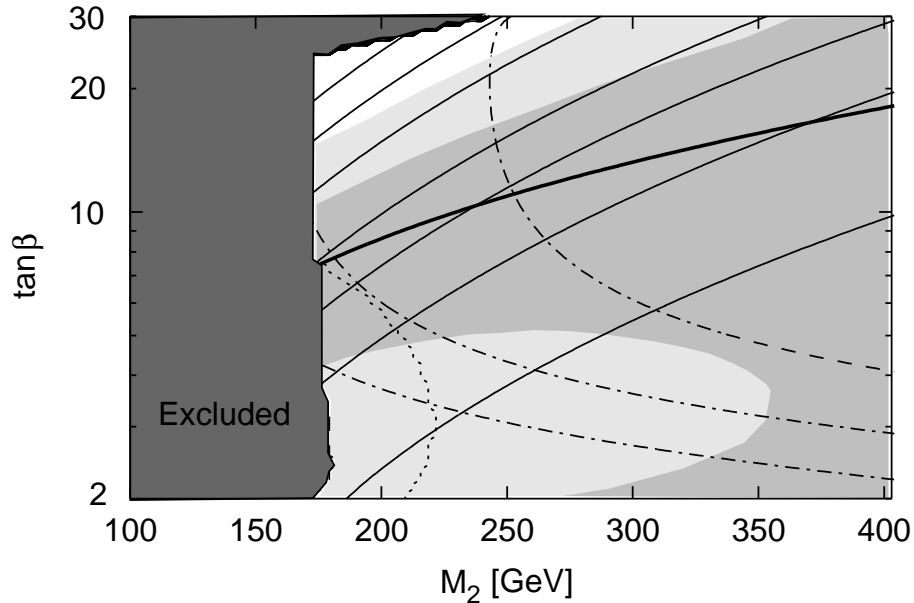
Figure 1: a_μ(SUSY) on the M_2 vs. $\tan\beta$ plane for $M_{\rm bc} = 2 \times 10^{16}$ GeV. The thin solid lines are for a_μ(SUSY) = 10, 20, 30, 40, 60, 80, and 100 in units of 10^{-10} (from below). The thick solid line is the contour for $Br(b \to s\gamma) = 3.15 \times 10^{-4}$, the center value measured by CLEO, and the darkly- and lightly-shaded regions are the parameter space consistent with $Br(b \to s\gamma) = (3.15 \pm 0.54) \times 10^{-4}$ and $2.0 \times 10^{-4} < Br(b \to s\gamma) < 4.5 \times 10^{-4}$, respectively. The contours of the constant Higgs mass ($m_h = 110$, 115 and 120 GeV, from below) are shown in the dash-dotted lines. The dotted line represents the contour of $m_{\tilde{\tau}_1} = m_{\chi_1}$; on the left-handed side of the dotted line, $m_{\tilde{\tau}_1} < m_{\chi_1}$ is realized. Regions with small M_2 and large $\tan\beta$ are excluded because of negative slepton mass and slepton mass smaller than the LEP bound, respectively; such regions are also shaded.

right-handed stau may become lighter than the lightest neutralino and may become the lightest superparticle in the MSSM sector [8]. Such a case should be cosmologically ruled out if the stau does not decay [13]. In Fig. 1, we also indicate the region where the stau becomes lighter than the lightest neutralino. Even after including these two constraints, we find that there is still a region in the parameter space which satisfies all the constraints.

Now, we would like to comment on the correlation between a_μ(SUSY) and $Br(b \to s\gamma)$. As was announced earlier, the relative sign of the gluino mass and the Wino mass plays an essential role. The chargino-sneutrino loop diagram dominates the SUSY contribution to the muon $g - 2$, and the sign of a_μ(SUSY) is correlated with that of $M_2\mu$; the muon magnetic moment receive positive and preferred contribution when $M_2\mu > 0$. On the other hand, as for $Br(b \to s\gamma)$, the SUSY contribution is mainly from chargino-stop loop diagram and its sign is correlated to the sign of $A_t\mu$ (where A_t is the trilinear scalar coupling of the stop sector). Since the sign of A_t is essentially controlled by that of the gluino mass M_3 through RG effects, the SUSY contribution to $Br(b \to s\gamma)$ interferes with the

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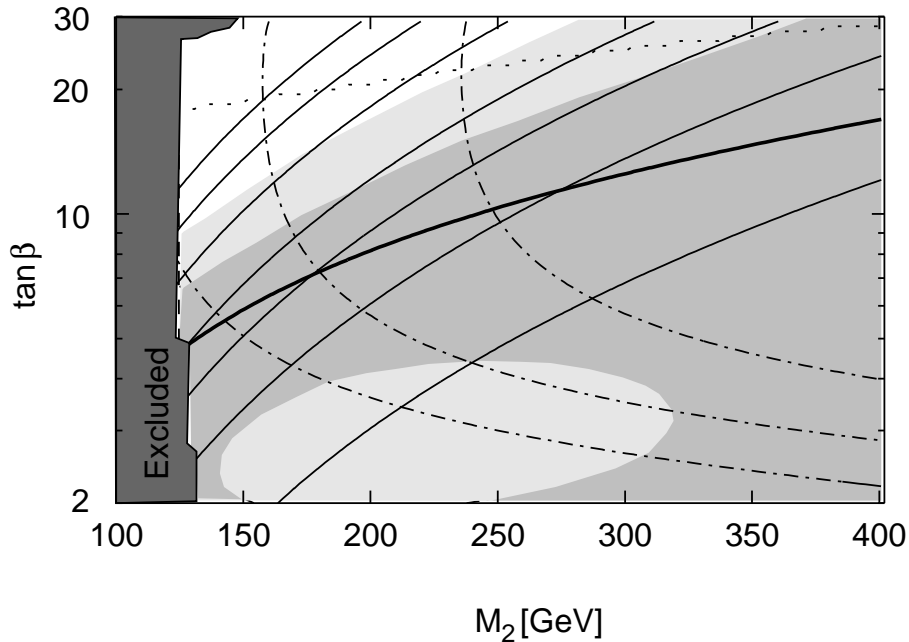Figure 2: Same as Fig. 1 except $M_{bc} = 10^{17}$ GeV. The excluded region at around $10 \lesssim \tan\beta \lesssim 20$ and 130 GeV $\lesssim M_2 \lesssim 150$GeV is due to the negative search for the right-handed stau.

contributions from the standard model and the charged-Higgs sector either constructively or destructively depending on the sign of M_3. The measured $Br(b \to s\gamma)$ is in good agreement with the standard-model prediction, and hence the negative interference is favored. It turns out that this corresponds to $M_3\mu > 0$. Thus, in the case of the universal gaugino mass where the sign of M_2 and M_3 is the same, one can choose the sign which is favored by the both measurements simultaneously.

Next, let us consider a case with higher M_{bc}. In Fig. 2, we show the same figure as Fig. 1 except that the RG flow starts at $M_{bc} = 10^{17}$ GeV. Above the GUT scale, we use the RG equations for the minimal SUSY $SU(5)$ model. Superparticle masses are affected by the RG effects above the GUT scale. In particular, above the GUT scale, the right-handed sleptons receive large (positive) mass corrections which are proportional to the gaugino mass because they belong to **10** representation in $SU(5)$ and hence the gaugino loop contribution has a large group factor. Other superparticle masses are not modified drastically. It is well-known that in this case the cosmological constraint, if we impose, becomes substantially weakend as in a wide region of the parameter space the stau is heavier than the lightest neutralino and the neutralino LSP is guaranteed [14]. On the contrary, the bounds from $b \to s\gamma$ and from the Higgs boson mass are almost unchanged when compared with Fig. 1. This is because these bounds are correlated to the squark masses, which do not significantly change when one includes the RG effects above the GUT scale.
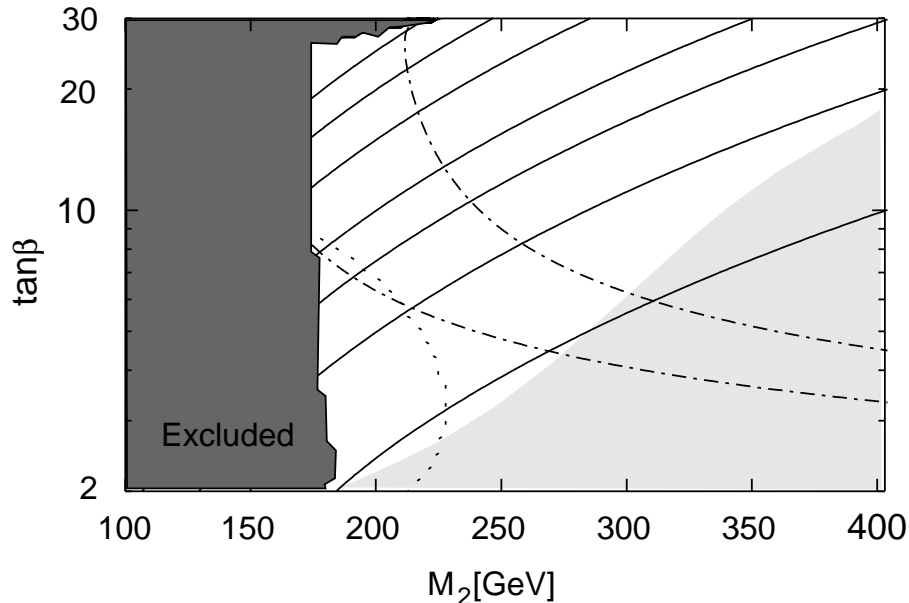
Figure 3: Same as Fig. 1 except $M_1^0 = M_2^0 = -M_3^0$.

As for a_μ, the region favored by a_μ is not changed drastically. This can be understood if one recalls that the dominant contribution comes from the chargino-sneutrino loop where the left-handed slepton mass plays an important role. In $SU(5)$, the left-handed sleptons are in $\mathbf{5}^*$ representation and below the GUT scale they are $SU(2)_L$ doublets, and thus the RG effect from the GUT region is not very important.

Thus our main conclusion is that the region favored by a_μ is completely overlapped with the region preferred by $Br(b \to s\gamma)$. This conclusion remains unchanged even when the RG flow starts above the GUT scale.

In order to demonstrate the importance of the relative sign of M_2 and M_3, we consider the case where gluino mass has an opposite sign to the other two gaugino masses; namely we take $M_1^0 = M_2^0 = -M_3^0$ with $M_{\rm bc} = 2 \times 10^{16}$ GeV, which results in $M_1 : M_2 : M_3 \approx 1 : 2 : -6$ at the electroweak scale. (For phenomenological discussions on the case of non-universal gaugino masses, see Ref. [15, 11].) The result is shown in Fig. 3. One can see that the overlap region preferred by both a_μ and $Br(b \to s\gamma)$ gets substantially reduced. This is because, in this case, taking $M_2\mu > 0$ for $a_\mu(\text{SUSY}) > 0$, the SUSY contribution to $Br(b \to s\gamma)$ constructively interferes with standard-model and charged-Higgs contributions. As a result, in order to suppress the effects of the charged-Higgs and chargino-stop loops, mass scale of the superparticles is required to be quite high and hence the region with small M_2 is disfavored in Fig. 3. Thus, unlike the universal gaugino mass case, the *correct* sign of M_2 from a_μ now gives the *wrong* sign of M_3 for $Br(b \to s\gamma)$ in this case. Besides, the Higgs mass bound constrains more severely than the previous case. This can be understood as follows. The left-right mixing mass in the stop sector has the form $m_t(A_t + \mu \cot\beta)$. In the present case where $M_3\mu < 0$ the two terms tend to cancel
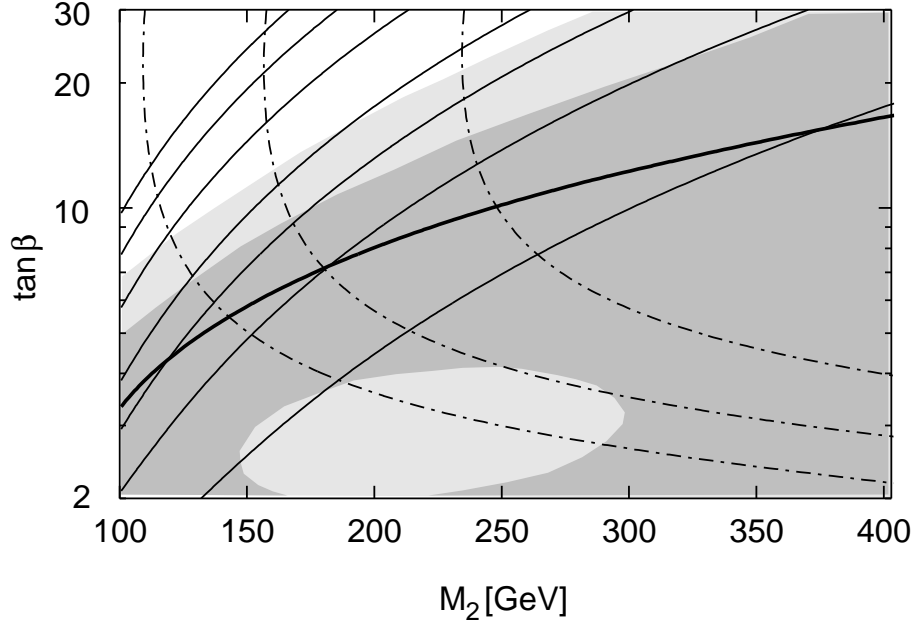
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Figure 4: Same as Fig. 1 except $M_1^0 : M_2^0 : M_3^0 = 3 : 1 : 1$.

each other. Thus the mixing term becomes small, reducing the radiative corrections from the stop-top sector to the Higgs boson mass. Combining the three constraints, preferred region remains only when the Wino mass is large, $M_2 \gtrsim 250$ GeV. If we further impose the cosmological constraint that the LSP should be neutral, then the preferred region completely disappears.

Let us next briefly discuss other examples of non-universal gaugino masses. When M_1 is much larger than M_2, the Wino can be the LSP. The result with $M_1^0 : M_2^0 : M_3^0 = 3 : 1 : 1$ is shown in Fig.4. In this case, the right-handed slepton masses are significantly pushed up since they originate to the $U(1)_Y$ gaugino mass. Consequently, the slepton mass bounds disappear (see Fig.4). On the contrary, masses of other sfermions are insensitive to the change of M_1 since they are from $SU(2)_L$ and/or $SU(3)_C$ gaugino mass parameters. As a result, one finds that the constraints on a_μ, $Br(b \to s\gamma)$ and the Higgs mass do not differ from the case of the universal gaugino mass (see Fig. 1).

Another example is the case with smaller M_3/M_2. In this case, for a fixed value of M_2, the RG effects on the squrak masses from the gluon-gluino loop becomes smaller and hence lighter squarks (in particular, lighter stops) are realized. This fact has an important implication; if the stops are light, the radiative corrections to the Higgs mass is suppressed. Thus, in order to evade the Higgs mass bound, overall mass scale is required to be pushed up. Then, the sleptons also become heavier and the SUSY contribution to the muon $g-2$ is suppressed. Therefore, for small M_3/M_2, constraints on the parameter space are severer. To demonstrate this point, we considered an example with $M_1^0 : M_2^0 : M_3^0 = 1 : 1 : 1/2$. We checked that, in this case, the Higgs mass bound severely constrains the parameter

space. Combining the 2-σ constraints on $a_\mu(\text{SUSY})$ and $Br(b \to s\gamma)$ with the Higgs mass bound $m_h \gtrsim 113.5$ GeV, we found that the parameter region with $\tan\beta \lesssim 7$ and $M_2 \lesssim 280$ GeV is excluded. Furthermore, if the 1-σ bound on $a_\mu(\text{SUSY})$ *or* $Br(b \to s\gamma)$ is used, there is no allowed region in the parameter space. Therefore, among the models with non-universal gaugino masses, scenarios with lighter gluino are severely constrained by the combined informations about $a_\mu(\text{SUSY})$, m_h and $Br(b \to s\gamma)$. Notice that there is another consequence of the lighter gluino. If M_3 is small, RG effects to the Higgs mass become smaller and hence the μ-parameter determined by the radiative electroweak symmetry breaking condition becomes smaller. In this case, higgsino contamination in the lightest neutralino is larger than the universal gaugino mass case.

In this paper, we considered the case of no-scale boundary conditions. We should stress here the interesting interplay between a_μ and $Br(b \to s\gamma)$ we observed in this paper is very generic and will be seen in many other classes of SUSY breaking models.

Finally, let us discuss possible improvements of the constraints in the future. A new result is expected from the E821 experiment with a improved statistics. If the error in $a_\mu(\text{E821})$ is reduced by a factor of 2 *without changing the center value*, $a_\mu(\text{SUSY})$ is within the range of $(27 - 59) \times 10^{-10}$ at the 1-σ level. In this case, the parameter space of the no-scale model is severely constrained. Importantly, when the gaugino masses obey the GUT relation, then even the region with $a_\mu(\text{SUSY}) = (27 - 59) \times 10^{-10}$ is consistent with the constraints from $Br(b \to s\gamma)$ and the Higgs mass (see Figs. 1 and 2). On the contrary, if M_2 and M_3 has opposite sign, then the parameter space is severely constrained. In the case with $M_1^0 = M_2^0 = -M_3^0$, for e.g., no allowed region remains even if we adopt the 95 % C.L. constraint from $Br(b \to s\gamma)$. In addition, more precise measurements of $Br(b \to s\gamma)$ has an important impact to constrain the scenario of the SUSY breaking, in particular if combined with the muon $g - 2$ anomaly. Therefore, improvements of the statistics in the measurement of the muon $g - 2$ as well as $Br(b \to s\gamma)$ will provide interesting and important informations in studying the scenarios of the SUSY breaking.

Note Added: In our analysis, we calculated the lightest Higgs mass using the one-loop effective potential given in Ref. [16]. In Ref. [17], the lightest Higgs mass is calculated taking account of two-loop contributions, and it is pointed out that the lightest Higgs mass tends to decrease due to the two-loop effect. The authors would like thank M.M. Nojiri for useful conversations.

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